

# Polarization of SN 1987A Revisited

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## ABSTRACT

The conventional picture for the origin of the polarization of a supernova is based on a model of Thomson or resonance scattering of photons traveling through an aspherical supernova atmosphere. Positive detection of intrinsic polarization in SN 1987A is then interpreted as evidence of an asymmetrical supernova atmosphere. We show here a different view based on the scattering of the supernova light by a dusty circumstellar material (CSM), or the “light echo” effect. At a given epoch after the explosion, the observed photons consist of both those propagating directly from the supernova and those scattered by dust particles in the CSM. Polarized light can be produced if the distribution of the dust particles is aspherical. The model can reproduce both the time evolution of the observed broad band polarization of SN 1987A and major features of the polarization spectra. It is also successful in providing a natural model for the early infrared light curve, in particular the observed 30 day delay of the IR maximum compared to the maximum of the bolometric light curve.

*Subject headings:* stars: individual (SN 1987A) – stars: supernovae

## 1. Introduction

Polarimetry of SN 1987A was obtained from 2–262 days after explosion (Jeffery 1991a, and references therein). Several groups (Jeffery 1991b; Höflich 1991) modelled the observations in terms of scattering by the supernova atmosphere (Sutherland & Shapiro 1982; McCall 1984). The degree of polarization predicted by these models is generally a decreasing function of time after explosion, as can be anticipated from the fact that the atmosphere gets progressively optically thin as the supernova atmosphere expands. Eventually electron scattering becomes unimportant and no polarization can be produced. These models are capable of reproducing the observations prior to day 100 after explosion (Höflich 1991; Jeffery 1991b). The observed degree of polarization, however, increased sharply from 0.2% to about 1.6% at around day 100 (Jeffery 1991a; Barret 1988). This behavior is difficult to reconcile in terms of the photospheric scattering model.

Correction for interstellar polarization (ISP) is crucial, but is unfortunately quite uncertain. We base our study on the polarimetric data compiled and corrected for ISP by Jeffery (1991a), where the ISP is estimated from unpublished observations made at La Plata Observatory at around day 600. The data show that the degree of polarization increased from about 0.1% at day 2 to about 1% at  $\sim$  day 250. The polarization position angle remains fairly constant during all these observations. The time variability of the polarization indicates that the observed polarization is intrinsically related to the supernova event, regardless of the ISP in the direction to the supernova.

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We show here that dust scattering plays an important role in producing the polarized light of SN 1987A. In §2.1 the survival of dust particles in the vicinity of the supernova is discussed. The dust scattering process and how that leads to the observed polarization is presented in §2.2. §3 compares the model with various observations. Conclusions and a brief discussion are given in §4.

## 2. The Model

### 2.1. Dust Survival

The dust particles in the vicinity of the supernova are destroyed mainly by the intense initial ultraviolet (UV) flash of the supernova after the shock breakout. Lundqvist & Fransson (1991), and Luo (1991) inferred that an initial UV flash with net energy  $\sim 6 \times 10^{45}$  ergs and effective temperatures  $\sim (3 - 6) \times 10^5$  K is required to fit the observed light curves of the various nebular emission lines of the circumstellar loops. The luminosities and radiation temperatures they used were taken from models 10H and 10L of Woosley (1988), and 11E1Y6 of Shigeyama, Nomoto & Hashimoto (1988). These models and also those by Arnett (1988) give peak luminosities of  $(2 - 3) \times 10^{44} \text{ erg s}^{-1}$  and peak effective temperatures of  $(2 - 5) \times 10^5$  K. More detailed models by Ensman & Burrows (1992) give peak luminosities  $(3.7 - 8) \times 10^{44} \text{ erg s}^{-1}$  and  $(5.5 - 7.2) \times 10^5$  K. The distance at which the dust achieves equilibrium temperature  $T_d$  is

$$r_d = \frac{1}{4} \sqrt{\frac{L}{\pi \sigma T_d^4} \frac{\langle Q(T_{sn}) \rangle}{\langle Q(T_d) \rangle}}, \quad (1)$$

where  $T_{sn}$  is the effective temperature of the supernova radiation,  $\langle Q(T) \rangle$  is the dust absorption efficiency averaged over wavelength and is a function of the effective temperature  $T$  of the radiation field, and  $L$  is the luminosity. Evaporation of dust particles occurs when  $T_d$  is above the evaporation temperature which is typically around 2000 K.

As Felten & Dwek (1989) noticed, however, the evaporation/sublimation time scale may be *longer* than the duration of the UV flash, and hence, dust can survive at a substantially smaller distance from the progenitor than given in equation (1). The time scale for dust evaporation at a temperature  $T_d$ , is (Voit 1992; Guhathakurta & Draine, 1989)

$$t_{ev} \sim (3 \times 10^{-11} \text{ s}) (a/1 \mu\text{m}) \exp [E_{\text{bind}}/kT_d], \quad (2)$$

where  $E_{\text{bind}}$  is the binding energy of the dust particles, and  $a$  is the radius of the dust particle. Guhathakurta & Drain (1989) give  $E_{\text{bind}} \approx 81,000$  K for graphite and  $E_{\text{bind}} \approx 68,100$  K for silicate. At  $T_d = 2000$  K,  $t_{ev}$  is  $\approx 10^{11}$  s, considerably larger than the duration of the UV flash which is  $\leq 2400$  s. Only grains heated up to a temperature at which the corresponding evaporation time is shorter than the duration of the UV flash will evaporate. The real temperature above which the dust particles will be destroyed is therefore given by equating  $t_{ev}$  and  $t_{UV}$ .

The radius beyond which the dust particles will survive as a function of the size of the dust particle is plotted in Fig. 1 for different models of the supernova explosions. This defines theoretically the minimum distance dust particles can survive the initial UV flash.

## 2.2. Dust Scattering

We define first a polar coordinate system of which the z-axis is along the line of sight and the x-axis is on the plane of sky and defines the zero point of the polarization position angle. The supernova is located at the origin. The number density of CSM dust is given by  $n(r, \theta, \phi)$ .

The scattered light depends sensitively on the shape of the supernova light curve. Consider first the case for which the supernova emits natural light at a luminosity per unit frequency  $L_\nu$  over a time  $dt_s$ . Assuming single scattering and  $0 \sim dt_s \ll t$ , the flux of the scattered light  $dF_\nu$  is derived by Chevalier (1986). The Stokes parameters  $dQ_\nu$  and  $dU_\nu$  can be found in a similar and straight forward way. The equations are

$$\begin{pmatrix} dF_\nu(t) \\ dQ_\nu(t) \\ dU_\nu(t) \end{pmatrix} = \begin{pmatrix} K_1(t) \\ K_2(t) \\ K_3(t) \end{pmatrix} L_\nu dt_s = \int_S dS \frac{n Q_s \sigma_d}{4\pi D^2} \frac{L_\nu dt_s}{4\pi r^2} \left| \frac{dz}{dt} \right| \begin{pmatrix} P_1(\theta) \\ P_2(\theta) \cos 2\phi \\ P_2(\theta) \sin 2\phi \end{pmatrix} \quad (3)$$

where the integration is over the plane of the sky,  $Q_s$  is the grain scattering efficiency,  $\sigma_d$  is the geometric cross section of the grain,  $D$  is the distance to the supernova, and  $P_1$  and  $P_2$  are elements of the dust scattering matrix (Chandrasekhar 1960) as a function of  $\theta$ . The scattering phase function  $P_1$  can be found in Henvey & Greenstein (1941), and the polarization function  $P_2$  approximates the Rayleigh function (White 1979).

For the more general case that the supernova light curve is given by  $L_\nu(t_s)$ , the fluxes and Stokes parameters can be obtained by convolving  $L_\nu(t_s)$  with  $K_1$ ,  $K_2$  and  $K_3$  (cf Chevalier, 1986). Scattered light contributes also to the observed luminosity, but is only a second order effect in the optically thin case. The net polarization of the supernova is therefore calculated by multiplying the polarization of the scattered light by the ratio of the scattered light to the luminosity of the supernova.

## 3. Comparing with Observations

Our most favored model is achieved by a dust blob of radius  $1.2 \times 10^{16}$  cm located on the plane of the sky passing through the supernova, at a distance  $5.7 \times 10^{16}$  cm away from the supernova and a position angle of  $15^\circ$ . The parameters governing dust scattering are: albedo  $\omega = 0.5$ , and peak linear polarization  $P_l = 0.5$ . The optical depth of the blob is 0.36. In the following this model is compared with observations.

### 3.1. Broad Band Polarimetry

We show in Fig. 2(a) the V band polarimetry together with the polarimetry curve calculated using equation (3). The V-band light curve is from Hamuy & Suntzeff (1990). The polarimetry data are from Jeffery (1991a). The degree of polarization scales linearly in the adopted optically thin approximation, and satisfactory fits were obtained for  $\tau \sim 0.2 - 0.5$ , depending sensitively on the distance to the supernova. The dust scattering asymmetry parameter is  $g = 0.3$  (Henvey & Greenstein 1941). The overall shape of the time evolution of the polarization is well reproduced. The increase of polarization before day 30 is due to the increase of the flux of the highly polarized scattered light as a result of light travel effects. The model

predicts an increase at around day 100 when the supernova evolves down from its second optical maximum. This behavior is again due to the fact that the fraction of scattered light increases as the supernova falls below its maximum.

### 3.2. Polarization Spectra

The broad spectral features in the polarization spectra which correspond to various absorption and emission lines of the supernova were taken as evidences against circumstellar scattering. We show here that this is incorrect. The observed polarization depends on both the intrinsic supernova light curve and the scattering process in a complicated way as shown in equations (3). Because the luminosities at different wavelengths evolve differently, the net polarization at different wavelengths will also be different, especially across strong P-Cygni lines. It can be anticipated that broad polarized spectral features can be produced. And indeed, as an example, Fig. 2(b) shows the model polarization spectra on day 100 obtained by using the set of spectroscopic observations of SN 1987A from the CTIO archive (Phillips et al. 1988). The model polarization spectrum agrees well with the polarization spectra corrected for ISP by Jeffery (1991a), considering the fact that the polarization spectra depends sensitively on the corrections for ISP.

### 3.3. Early Infrared Emission

The dust particles responsible for the scattering and polarization emit also in the infrared. The infrared light curve is calculated by assuming  $g = 0$  for the dust scattering phase function. Fig. 3 shows the model results together with the luminosity of the IR component obtained by fitting two black bodies to the early photometric observations (Bouchet et al. 1989). Although Bouchet et al. (1989) argue that the infrared emissions may come from free-free emission of the supernova ejecta, the present model correctly fits the light curve of the infrared emission, in particular the time delay of its maximum compared with the observed light curve. Note that the temperature of the dust particles varies with the distance to the supernova, so their emission can not be exactly that of a black body. A self-consistent analysis requires detailed modeling of the dust emission and the early observations which is beyond the scope of this paper. It is encouraging that such a simple analysis already yields surprisingly satisfactory model fits.

## 4. Discussions and Conclusions

The polarimetry of SN 1987A can be modeled in terms of scattering by a dusty blob. Both the polarimetry curve and the early infrared light curve can be successfully fitted by a CSM dust scattering blob.

This analysis is, however, far from complete. Substantial improvements can be achieved by more detailed modeling. In particular, the polarization position angle also shows clear changes across spectral lines. This suggests that a single scattering blob can not account for all the observed polarization. Two or more blobs may improve the model. Another possibility is that the observed polarization is a combination of the atmospheric scattering model and the CSM dust scattering model presented here.

The hypothesized dust blob may be related with the mystery spot discovered in earlier speckle observations (Cropper et al. 1988). They are located at almost identical position angles of  $\sim 15^\circ$ . Further analysis may provide some interesting tests for the authenticity of the speckle sources (Nisenson et al. 1988; Meikle

et al. 1987).

Our recent observations show that polarization  $\sim 1\%$  may be a common phenomena in Type II supernovae (Wang et al. 1996). A correct picture for the origin of the polarization is therefore critical for the understanding of supernova explosion mechanisms in general, and also in establishing Type II supernovae as extra-galactic distance indicators using the expanding photosphere method. If dust scattering is really important in producing polarization, the present study suggests that Type II supernovae are more likely to be associated with CSM dust than Type Ia. It is especially likely that dust scattering plays a role in SN 1993J which was strongly polarized and has a substantial CSM. Polarization measurement can thus set strong constraint on the environment of supernovae (Wang & Wheeler 1996).

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## Figure Captions

**Fig. 1** Dust survival radius for different supernova explosion models. The luminosities (in units of  $10^{44}$  erg/sec) and durations (in seconds) of the out-burst were approximated as: 5, 20 (500full1), 2.3, 200 (11E1Y6), and 0.35, 2400 (10H), respectively. The effective temperature of the out-burst was taken as  $5.0 \times 10^5$  K for all of the models. The dust absorption coefficients were taken from Draine & Lee (1984).

**Fig. 2** (a) V band polarimetry of SN 1987A; (b) Polarization spectrum at day 100.

**Fig. 3** Early infrared observations. The bolometric luminosity was scaled down by a factor of 10 for clarity.







